A review of electrode design for electrochemical drilling and electropolishing of holes

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ABSTRACT
This paper reviews the development of high-efficiency and low-cost electrode for electrochemical drilling and electropolishing of holes. Holes are major feature in die and mold. The design logic chart of the electrodes to address the major technical issues is presented, along with the electrode shapes and the representative experimental results. For the electrochemical drilling, it is concluded that a slow relative rotary motion between the electrodes helps to produce the machined profile of better quality. During electrochemical drilling, the use of bit type of tools produces more accurate holes as compared to bare type of tools. Comparing the anode corner profiles computed by cosine method and feed rate interpolation with the experimentally obtained anode corner profiles, one realizes the design of the cathode shape to achieve a required anode shape is a primary concern in electrochemical drilling. For the electropolishing of holes, the completely inserted, feeding, and rib plate electrodes are connected with continuous direct current. The controlled factors include the diameter of the electrode, the chemical composition and the concentration of the electrolyte. The experimental parameters include electrical current density, current rating, electrode design, die material, rotational speed of electrode, polishing time, and electrode feed rate. The completely inserted electrode with helix discharge flute performs better than that without flute or with straight flute.

The feeding electrode of borer type performs better than that with a lip on the leading edge. The rib plate electrode of single rib plate on one side with slant discharge flute has more space for dregs discharge and also reduces the secondary machining, thus performs the best polishing.

KEYWORDS: electrochemical drilling, electropolishing, electrode design, surface roughness

1. INTRODUCTION
Faraday made use of the electrical and chemical energy to remove materials and presented the principle of electrochemical machining in the eighteenth century [1]. Gusseff first filed a patent on electrochemical machining (ECM) in 1929. Later he found that ECM is suitable for alloy of high strength and high melting point. Noto et al. put forward the study of the electrode gap and the associated control of workpiece geometry in the electrochemical machining [2]. More industrial applications were realized throughout the decades, such as electrochemical drilling, electrochemical grinding, electrochemical deburring, and electropolishing [3]. Phillips found the major factors in the removal rate of electrochemical grinding are the conductivity of the workpiece, the rate of decomposition, the current capacity of power supply, and the composition, concentration, and temperature of electrolyte. The experimental results of Mileham et al. showed the quality of the
The machined surface will be influenced by the current density, flow rate of electrolyte and the gap width [4]. Bannard correlates the current efficiency with current density and flow rate of electrolyte. The maximum efficiency varies with the type of electrolyte [5]. Datta showed that the gap width between electrode and workpiece directly influences the current condition and the discharge drag of the electrolyte [6].

The electropolishing can efficiently produce workpieces of good surface finish. It is well suitable for difficult-to-machine materials. Plastic or press dies, wire-drawing dies, optical and electric parts can apply this technique as well [7]. The electrochemical honing of cylindrical holes improves the dimensional accuracy and relieves the surface layer stress [8]. Bejar et al. changed the machining gap width as well as the concentration of electrolyte to investigate the influence upon current efficiency. They found that the electrical current efficiency is raised with the increase of current density and electrolytic concentration [9]. Shen used NaNO₃ as the electrolyte to conduct the electropolishing on die surface. The result showed that the surface roughness of workpieces decreases with the increase of current density, flow rate and concentration of electrolyte. Moreover, polishing with pulse direct current is found better than continuous direct current [10]. The average surface roughness of common die materials from rough turning is about 3.0 to 6.3μm, and better surface roughness of 0.8 to 1.6μm can be obtained following careful fine turning [11]. However, surface finish finer than 0.8μm is often required for mechanical parts, thus the subsequent conventional techniques such as polishing by hand or machine are applied. These operations heavily depend on the sophisticated experience, and either hand or machine polishing will result in nonuniform residual stress due to the contact between tool and workpiece. Surface crack and micro voids are often induced and deteriorate the service life. The electropolishing can efficiently produce workpieces free of the above-mentioned shortcomings [7].

Hole making is essential for die and mold and other high-performance parts while challenging to electrochemical machining due to the limited space for dregs discharge. The development of an effective and low-cost tool electrode is critical in a successful electrochemical machining of holes, including electrochemical drilling and electropolishing. In the following, the technological progress in this aspect will be reviewed.

2. Tool design in electrochemical drilling

The pursuit for fine machining facilities, cost control, production management, and other aspects will be in vain if the manufacturer does not possess the competence to design ECM tools. It is often called an “art”, since much information has evolved by empirical development of tooling, and some “tricks” of tool design do work but are not always supported by logical explanation. An “art” implies the skills acquired by tedious trials and errors, hardly compatible with the pace of modern industry. However, even with a precise design guideline, the success still depends on special knowledge and experiments [3]. Tool design in ECM depends on the prediction of anode (workpiece) shape obtained from a tool under specified conditions of machining. The produced shape by ECM under ideal conditions can be computed from the corresponding equilibrium gap. The results are influenced by a large number of parameters, such as the presence of an anodic film, the current density, the electrode feed rate, change in valence of the work material during machining, the type of electrolyte and the role of additives, the electrolyte pressure distribution, and the electrolyte throwing power.

In hole making, a longitudinal section of the typical hole produced in electrochemical drilling (ECD) using a cylindrical tool is shown in Fig. 1. The deviation between the intended and the actual obtained hole profile depends upon the machining conditions employed. However, based on the nature of electrolyte flow, the hole section can be divided into four zones as shown: front, side, stagnation and transition. The hole thus produced would have tapered walls and be over cut.
To produce a straight-wall hole, the tool profile must be corrected. The extent of profile correction required to obtain a straight hole is rather difficult to compute accurately. This problem becomes more acute if complex shaped components are to be manufactured. Problems of ECM tool design have been highlighted by Jain and Pandey [12].

Electrochemical drilling with stationary electrodes produces an inaccurate and irregular hole profile. The effect of electrode rotation on the hole shape at different voltage can be seen in Fig. 2. When NaCl is used as the electrolyte, the electrode rotational speed has little effect on the rate of metal removal, but its effect on the over cut and the circularity of the hole is significant. It can also be seen that at the electrode rotational speed of 65rpm, the magnitude of over cut in all cases is larger than obtained at 0.9 and 1.2rpm. This can be attributed to the rotational effect of the electrode leading to efficient convective transfer of oxide material off the workpiece by centrifugal action. The effect of low speed workpiece (anode) rotation on the accuracy of hole reproduction and other related parameters in ECD has been studied.

Fig. 2. Effect of voltage and rotational speed of workpiece on metal removal rate. Electrolyte: 10\% NaCl; flow rate: 6.05 liters min$^{-1}$; flow velocity: 3.73 ms$^{-1}$; Do=7.62mm; Di=4.9mm; feed rate: 0.28mm min$^{-1}$; pressure: 0.16N mm$^{-2}$ [12].
A theoretical analysis of the effect of workpiece rotation and electrolyte flow velocity is presented. It is concluded that a slow relative rotary motion between the electrodes helps to produce a better hole profile. At high rotational speeds, the amount of over cut increases [13].

Fig. 3 shows the hole sinking operation with the electrode divided into four different regions. Most of the work available in the literature pertains to the front and side gaps (zones 2 and 4) only, whereas little information is available about the mode of material removal in the transient and stagnation regions (zone 1 and 3) [13]. It is equally important to know the anode profiles in transition zone and stagnation zone, apart from front and side zones. Few efforts have yet been made to study the complete anode profile as a single entity, Fig. 4. More realistic prediction of anode profile would eventually improve the quality of a product through tooling design procedure. During electrochemical drilling, the use of bit type of tools produces more accurate holes as compared to bare type of tools. However, no model is available to predict anode profile, obtained during electrochemical bit drilling (ECBD). The models of one dimensional analysis and two dimensional analysis based on finite element technique have been proposed. The models are capable to predict the workpiece shape and size obtained either by bit type or bare type of tool. The models can simulate both types of workpieces, i.e. the workpiece with or without a predrilled hole. Some assumptions

![Figure 3. Schematic diagram of ECD with outward mode of electrolyte flow. Zone 1 (stagnation), Zone 2 (front), Zone 3 (transition) and Zone 4 (side) [13].](image)

made in earlier models regarding zero void fraction, constant electrolyte flow, zero feed rate in transition and side zones etc. have been relaxed. Special attention has been paid to the analysis of anode profile in the transition zone and its effects on the accuracy of the computed anode profile in side zone. Comparison of analytical and experimental anode profiles has revealed a good agreement between the two. Transition zone has been discretized into small elements with the sides of a quarter of a regular polygon (see Fig. 5). Finer elements size produces better convergence. The anode corner profiles computed by cosine method and feed rate interpolation were compared with the experimentally obtained anode corner profiles, thus the design of the cathode shape to achieve a required anode shape is found a primary concern in ECM. The basic ‘cosine rule’ has been used for solution [14].

3. Tool design in electropolishing

The potential for electropolishing is yet to explore, the main difficulty lies in the design and manufacture of tool electrode. The have been the inserted, feeding, and rib plate electrodes developed for electropolishing holes [15-17]. The current study major discusses the development and performance of electrode design in electropolishing of hole.

An efficient polishing process using low-cost electrodes considering the following aspects can be achieved.

(1) Dimension of hole

For small and medium holes, a completely inserted electrode and a feeding electrode are proposed [15-16]. The inserted electrode polishes the whole surface of the hole wall at one time, the production cycle time is kept short. For the feeding electrode, higher electrical current is not required as the electrode engages the hole in small area during polishing. To reduce the cost of the power supply, the feeding electrode can be employed at the expense of the increased cycle time. One notices the discharge of the electrolytic product is more advantageous in use of feeding electrode. For medium and large holes, a completely inserted electrode of the rib plate is proposed [17]. The whole surface of the cylindrical walls is polished at one time, hence the production cycle is kept short. The discharge of the electrolytic product is satisfactory in this case, important for large-area electrochemical machining.

(2) Increasing current density to provide fast tool feed

Since the electropolishing requires a sufficient electrical current density, good electrode design should meet this requirement. Small end radius or sharp inner edge rounding of electrodes leads to high current density and feed rate.

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**Fig. 5.** Discretization of transition zone associated with the two type of tools (a) round cornered tool, (b) sharp cornered tool [14].
(3) Effective discharge of electrolytic products
The discharge of the electrolytic products out of the gap is crucial for the polishing. The open space provided by straight and helix flute, large angle, and thin cross section will be incorporated into the tool design.

(4) Reducing secondary machining
To ensure the dimensional and geometrical accuracy of the polished hole surface, the secondary over cut induced from the working gap should be eliminated as possible.

(5) Cost and manufacture of the electrodes
The electropolishing should design electrodes whenever the cost of the production of the electrode will cause no extra concern.

The review of classification of the electrode design is shown in Fig. 6 [15-17]. The design logic flow chart of the development of the electrodes for hole polishing is divided into three categories: completely inserted, feeding, and rib plate electrodes, as illustrated in Fig. 7-9. The geometry of the electrodes is shown in Fig. 10-12 [15-17].

4. Experimental results of electropolishing holes

4.1 Experimental set-up
The equipment of electropolishing includes DC power supply, pump, flow meter, electrolytic tank, and filter. The representative experimental set-up is schematically illustrated in Fig. 13 [15-17]. The materials of workpiece are SKD11, SKD61, NAK80, and SNCM8. The chemical compositions are shown in Table 1. The amount of the reduction of dimension after electropolishing is 0.2mm depending on the adopted feed rate of electrode and the adopted current density. The initial average surface roughness of the workpiece is 3.5 ~ 4.5 μm, the aim is to reduce the value to

![Diagram showing electrode category of electropolishing]

Fig. 6. Category of electrode design in electropolishing of holes.
Electrode design for electropolishing holes

Fig. 7. Development of inserted electrode design for electropolishing of hole [15-16].

below 0.8μm. The main parameters include the geometry of electrode, die material, and the electrode feed rate. The electrolyte is NaNO₃ of 25%wt. The reason of using NaNO₃ lies in that it is quite stable and suitable for a certain amount of material removal eliminating the need for complicated pre-polishing of workpiece. The flow rate of electrolyte is 4l/min. The temperature of the machining is maintained at 25±5°C. The gap width between electrode and workpiece is set 0.3mm. The current rating is 10A. The rotational speed of workpiece is 200, 400, 600, 800, 1000,
1200, and 1400rpm. The axial feed rate of the electrode ranges from 0.5 to 4.0mm/min. The produced surface roughness is measured at more than two locations by Hommel T500 with the accuracy of ±5%. The representative results of surface finish of electropolishing developed with design electrodes of internal cylindrical surface is illustrated in next section from Fig. 14 to Fig. 19.

4.2 Electropolishing of small-to-medium hole by completely inserted electrodes

Fig. 14 [15] shows the electropolishing with different types of inserted electrodes. Type A1 of the simplest
form provides the mediocre effect. One finds that the flute on the electrode elevates the polishing effect. It is closely related to its capability of discharging electrolytic dregs, and the effect varies with different types of flute. The polishing effect of electrode with discharge flute is significantly improved compared to the simple cylinder electrode. Further investigation shows the helix flute (type Ci) is better than straight flute (type Bi). The electrode with water-hole (type Fi) enhances the electrolyte circulation and the flushing of dregs, since it provides guided flow of the electrolyte with higher velocity. Hence type Fi performs the best among the six inserted electrodes.

The improvement of surface roughness using different completely inserted electrodes can be observed in Fig. 14. For instance, the improvement obtained by Fi (helix flute with water-hole and rotational) over the simple straight cylinder is nearly 70%. Fig. 15 [15] shows the share of the
surface roughness improvement obtained by $F_i$ through the major factors of electrode such as rotation (25%), helix flute (33%), and the water hole (42%). In summary, the electrode design features of water hole and helix flute contributes the most to the polishing.

4.3 Electropolishing of deep hole by feeding electrodes

Limited by the dregs discharge, the completely inserted electrodes cannot work well in a deep hole. A feeding electrode becomes necessary. The tested diameter of the hole to be polished in the current experiment is a medium of 8.0mm, the same as the above section, while it can be increased to larger hole without difficulty. Fig. 16 [16] shows the electropolishing with different feeding electrodes for various materials, the polishing of SKD61 is the best, followed by SKD11, NAK80, and SNCM8. As comparing

Fig. 10. Design of inserted electrode design for electropolishing of hole [15-16].
the electropolishing through different feeding electrodes, the results also show that among the six types of electrode, the electrode type $F_r$ gives the best surface finish. The electrode $A_r$ has a circle lip on the leading edge of the cylinder. The electrode $B_r$ has a repolishing effect since the edge is made of two cycle lips. Electrode type $C_r$ can actually operate at higher current density, since the edge of the lip has an end radius leading to a concentrated electrical current distribution. Electrode type $E_r$ with one borer tip provides more open space of dregs discharge than the electrode $D_r$ of two borer tips. Electrode type $F_r$ has a ball-shape borer tip with more space for dregs discharge than the above three electrodes with full circle lip performs the best among all electrodes.
Fig. 12. Design of rib electrode design for electropolishing of hole [17].

Fig. 17 [16] shows the contribution share of surface finish improvement obtained by the design features of Fr, through the circle lip (12%), end radius (22%), and the borer feature (66%). One finds that a good design of the electrode form in electropolishing using the borer feature is very effective.

4.4 Electropolishing of medium-to-large hole by rib-plate inserted electrodes
At the same amount of hole diameter enlargement of 0.2mm during electropolishing, various materials show different material removal rates in the process, whereas the achieved surface finish depends on the electrode design on the other hand. The required
Electrode design for electropolishing holes

(a) System schematics

(b) Configuration of tool and workpiece

Fig. 13. Schematics of experimental set-up [15-17].
Table 1. Chemical Composition of Workpiece

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<tr>
<th>(Wt %)</th>
<th>Fe</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>V</th>
<th>Cu</th>
<th>Ni</th>
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<td>SKD61</td>
<td>90.70</td>
<td>0.38</td>
<td>0.96</td>
<td>0.43</td>
<td>0.29</td>
<td>0.03</td>
<td>5.31</td>
<td>1.08</td>
<td>/</td>
<td>0.82</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>SKD11</td>
<td>88.65</td>
<td>1.40</td>
<td>0.40</td>
<td>0.30</td>
<td>0.02</td>
<td>0.03</td>
<td>8.20</td>
<td>0.80</td>
<td>/</td>
<td>0.20</td>
<td>/</td>
<td>/</td>
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<tr>
<td>NAK80</td>
<td>92.06</td>
<td>0.13</td>
<td>0.60</td>
<td>1.50</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>0.25</td>
<td>1.12</td>
<td>/</td>
<td>1.24</td>
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<tr>
<td>SNCM8</td>
<td>96.48</td>
<td>0.39</td>
<td>0.30</td>
<td>0.90</td>
<td>0.02</td>
<td>0.03</td>
<td>0.80</td>
<td>0.25</td>
<td>/</td>
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</tbody>
</table>

Fig. 14. Electropolishing with different inserted electrodes (SKD61, 41/min, continuous DC, 30A/cm², 30 sec) [15].

Machining time for different materials varies as follows: SKD61 30 seconds, SKD11 35 seconds, NAK80 40 seconds, and 50 seconds for SNCM8 (see Fig. 18 [17]). One finds SKD61 is machined in the shortest time, and its polishing effect is the best. In the electropolishing with different types of rib plate electrodes, the electrode Ar is the simplest plate-form providing the mediocre effect. Type Br with double lips on the edge of the plate actually operates at higher current density, since the edge of the lip has a retreat instead of a full front producing more concentrated electrical current. The second lip also produces a repolishing effect, which is slightly more advantageous over the electrode Ar. Type Cr has a wedge edge, which provides more open space of dregs discharge than the above two electrodes. Electrode Dr with small long wedge toward to the root of the plate provides more efficient discharge, which is advantageous for polishing. Type Er with single rib plate obviously has much more space for dregs discharge and also reduces the secondary
Electrode design for electropolishing holes

Fig. 15. The contribution pie of surface roughness improvement of electrode Fi (SKD61, 41/min, continuous DC, 30A/cm², 30 sec) [15].

Fig. 16. Electropolishing with different feeling electrodes for various materials (41/min, continuous DC, 10A, 2 mm/min) [16].

Fig. 17. The contribution pie of surface roughness improvement of electrode Ff (SKD61, 41/min, 600 rpm, continuous DC, 10A, 2mm/min) [16].
machining, so that the polishing effect of electrode Er performs better than those with double plates. Type Fr of single plate with slant discharge flute performs the best among the six electrodes, because its single plate provides more sufficient flushing space, thus the dregs are more quickly discharged out of the gap and elevates the polishing effect. The slant discharge flute can assist to transmit the electrolyte product in more guided hence efficient way along the flute. Based on the above results, the authors can assess the contributions of surface finish improvement (see Fig. 19 [17]) obtained by type Fr through the application of the edge rounding radius (26%), the wedge angle (41%), and the slant discharge flute (33%). In summary, the electrode design of wedge angle and slant discharge flute contributes the most to the polishing.

Fig. 18. Electropolishing with different rib electrodes at 0.2mm of diameter enlargement (41/min, continuous DC, 30A/cm²) [17].

Fig. 19. The contribution pie of surface roughness improvement of electrode Fr (SKD61, 41/min, continuous DC, 30A/cm²) [17].
5. CONCLUSIONS

For the electrochemical drilling, a slow relative rotary motion between the electrodes helps to produce a fine hole profile. The use of bit type of tools produces more accurate holes as compared to bare type of tools. The basic ‘cosine rule’ has been used for the design of the cathode shape to achieve a required anode shape, which is a primary concern in electrochemical drilling. The review of the designed electrodes reveals a wide area in advancing the technology of electropolishing. It offers the advantages of using economic equipment, low-cost process, and controllable material removal compared with the conventional ECM. The process fast improves the surface roughness of workpiece. Among the commonly used die materials, SKD61 shows the best surface finish in electropolishing, followed by SKD11, NAK80, and SNCM8. The completely inserted electrode with discharge flute for polishing holes significantly improves the surface finish. The helix flute performs better than the straight flute. Water hole in the electrode is effective. The electrode of bore feature performs better than that with a cycle lip on the leading edge. The inserted electrodes are suitable for small or medium holes, while the feeding electrodes can be used for large or deep holes. The working time for the former is short provided the power supply is sufficient. The polishing of the rib type electrode of single rib plate with slant discharge flute has good dregs discharge effect and also reduces the secondary machining, thus performs the best polishing. In summary, the design of electrode contributes significantly to the polishing results, compared to the processing parameters. An adequate electrode design associated with the optimal operation parameters can achieve the considerable improvement of surface finish beyond the conventional machining.

REFERENCES